UTILIZATION AND ECONOMIC POTENTIAL OF DIFFERENT URANIUMS IN LMFBRS

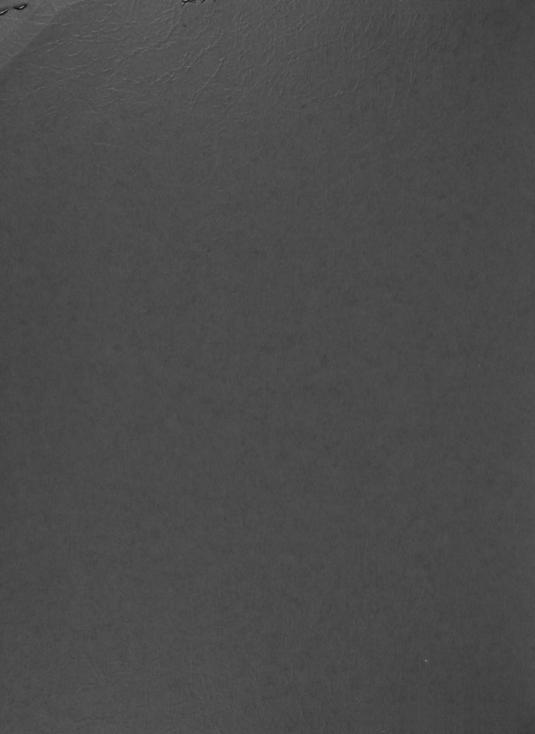
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Utilization and Economic Potential of Different Uraniums in LMFBRs

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ARSTRACT

Under certain conditions, it is more economical to use natural uranium instead of depleted uranium in LMFBRs. The use of natural uranium is restricted to the core region. A critical residence time T_{crit} is determined such that the costs for fuel inventory and consumption are the same in a LMFBR with natural uranium and one using depleted uranium. An optimum residence time T is defined such that the cost benefits for using natural instead of depleted uranium are maximized. It was shown that large LMFBRs (>800 MWe) permit T_{crit} values of three years and less. Optimum residence times are of the order of six to seven years. T_{crit} and T_{opt} increase for smaller reactor sizes. Both times depend very strongly on the price for 235U and to a lesser extent on the interest rate. For residence times greater than T_{crit}, savings in inventory and consumption costs of several percent can be expected by replacing depleted uranium by natural uranium.

Utilization and Economic Potential of Different Uraniums in LMFBRs

INTRODUCTION

Current LMFBR fuel designs use mixed uranium-plutonium oxide ($\rm UO_2$ -PuO_2) as fuel. The isotopic composition of plutonium is that of LWR discharge plutonium. The uranium used is depleted uranium with an assumed composition of 0.3% 235 U and 99.7% 238 U. The reason for using depleted uranium rather than natural or enriched uranium is the low cost of this material which is considered negligible compared to the plutonium cost. At a price of \$8/lb $\rm U_3O_8$ the cost of 235 U in natural uranium is of the order of \$3/g. The cost for the conversion of $\rm U_3O_8$ to $\rm UO_2$ in the case of natural uranium and UF_6 to $\rm UO_2$ in the case of depleted uranium are of the same order of magnitude. Table 1 shows these conversion costs for different plant sizes.

In large plant sizes, these costs are less than $\$0.50/g^{235}U$. A price of \$10/g is commonly used as price for fissile plutonium (^{239}Pu and ^{241}Pu). This already illustrates that under certain conditions, it might be advantageous to use natural uranium instead of depleted uranium in LMFBRs. But we have to expect that the burnup of ^{235}U as well as the interest rate and the price for U_3O_8 will affect the economics of the utilization of natural vs depleted uranium in LMFBRs.

2. REACTOR MODEL

Two reactor sizes have been chosen: one reactor is in the area of 500 MWt and the other reactor is of the order of 2000 MWt (core plus radial blanket only). Descriptions of these reactors are given in Table 2. Earlier calculations for reactors with natural uranium in the radial blanket indicated that long residence times would be required to justify its use.

MOTTOUGONTHE LE

Correct CATES fuel designs use mised prentum-plurantum estate (Mog-Pup) as fuel. The isotopic composition of plutonium is that of the discharge plutonium. The uranium used is depleted prentum with an assumed composition of 0.3% ²³⁵U and 59.7% ²³⁸U. The reason for using depleted prantum cather than natural or enriched wrantum is the low cost of Unis material which is considered negligible compared to the plutonium cost. At a price of 30/lb U₂O₂ the cost of ²³²U in natural brenium is or the order of the cost of using the cost of depleted underline are of the Same order of magnitude. Table 1 shows these conversion costs for different plant sizes.

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TABLE 1. Conversion Cost Estimates

("Reactor Fuel Cycle Costs for Nuclear Power Evaluation," WASH-1099, December 1971)

Heatel Slave	Plant Capacity Mt/day	Capital Investment (\$10 ⁶)	Annual Operating Cost, (\$10 ⁶)
Actor back	19. 00-1	0.000	0.0006
UF ₆ → UO ₃	1 10 30	2.54 7.53 13.4	0.615 1.91 3.91
U ₃ O ₈ → UO ₃	0.907 9.07 27.2	2.06 5.36 9.40	0.425 1.12 2.51
UO ₃ → UO ₂	10	1.11 3.41	0.364

TABLE 1. Conversion Cost Estimates

("Reactor Fuel Cycle Costs for Muclear Power Evaluation," UASH-1099, December 1971)

TABLE 2. Reactor Descriptions

MWt	500	2000
mial direction say annearming by a leave	ng siety.	
Core radius, cm	60	120
Core height, cm	92	92
Radial blanket thickness, cm	20	20
Reflector thickness, cm	10	10
Axial buckling, cm ⁻²	0.00056	0.00056
Core composition stainless steel, % fuel, % sodium, %	24 35 41	24 35 41
Blanket composition stainless steel, % fuel, % sodium, %	15 50 35	15 50 35
Reflector stainless steel, % sodium, %	85 15	85 15
Plutonium composition Pu-239, % Pu-240, %	88 12	88 12
Fuel density, smeared (85% T.D.), g/cc	9.35	9.35
Excess reactivity, % \(\Delta k / k \)	5.0	3.0

TABLE 2. Resittor Descriptions

Since current designs have upper and lower axial blankets as integral part of the fuel pin, the residence times for axial blankets are the core fuel residence times by definition. Therefore, the use of natural instead of depleted uranium in the axial blanket has not been analyzed and the axial direction was represented by a buckling only.

To avoid unnecessary complications, single-zone cores without control poison were analyzed.

3. CALCULATIONAL APPROACH

The use of natural uranium in LMFBRs instead of depleted uranium can be accommodated in three ways:

- (a) natural uranium in the core, depleted uranium in the blanket;
- (b) depleted uranium in the core, natural uranium in the blanket;
- (c) natural uranium in core and blanket.

To assess the significance of reactor size, a LMFBR with a core and radial blanket power of 500 MWt and one with 2000 MWt were considered. They will be called 500 MWt and 2000 MWt LMFBR.

Table 3 shows the various combinations of natural and depleted uranium which were analyzed. The comparison of the economics of the two fuel types is done by comparing the cost of fuel inventory and consumption (a production). The use of natural uranium instead of depleted uranium leads to a reduction of plutonium inventory and consumption. On the other hand, there are the total costs for natural uranium (principal plus interest) which have to be balanced by savings to justify its use. It is assumed that the natural uranium whenever discharged from the reactor has a zero value. This points already to the burnup as a very important parameter in this assessment. If the burnup of natural uranium is such that only a small fraction

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 - c) matural uranium in core and blanket.

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TABLE 3. List of Cases Which Were Analyzed

	The family of that	Uranium Composition					
Case	Reactor Size, MWt	Core	Blanket				
1	500	D	D				
2		N	D				
3	for the second	D	N				
4		· N	N				
5	2000	D	D				
6	ALCOHOL IN THE STATE OF THE STA	N	D				
7		D	N				
8		N	N				

D = natural uranium

N = depleted uranium

FABLE 3. List of Cases Which Were Analyzed

D = natural urantum N = depleted urantum of 235 U is burned then one cannot expect an improvement in economics. On the other hand, if it were possible to burn all 235 U then the economics of utilizing natural uranium were virtually guaranteed. The reference cost for fissile plutonium in oxide form is 10 gr fissile Pu and for 235 U it is $^{3.50}$ gr 235 U. The calculations were performed with REBUS $^{(2)}$ and DIF1D. $^{(2)}$ I did not consider the potential for improving the burnup capability of the fuel by increasing the number of fissions in uranium as observed in irradiation experiments 3 since this effect cannot be described quantitatively at the present time.

4. ECONOMICS EQUATIONS AND CRITICAL RESIDENCE TIME

In the following, the various cost components will be discussed which are of importance for the assessment of natural vs depleted uranium in LMFBRs.

We assume that the plutonium inventory I changes linearly with time. With $\delta I...$ annual change in plutonium inventory in kg, T... cycle time in calendar years, $I_0...$ initial plutonium inventory in kg, we obtain

$$I(T) = I_0 - T\delta I . (1)$$

Neglecting out-of-pile inventories, the average plutonium inventory $\overline{\mathbf{I}}$ can then be written as

$$\overline{I} = I_0 - \frac{1}{2} T \delta I \qquad . \tag{2}$$

The change in plutonium inventory G over T years is

$$G = T\delta I . (3)$$

Since the uranium discharged from the reactor will not be used again, the average uranium inventory \overline{F} is one-half of the total uranium inventory $F_0(kg)$ or

of 233U is burned then one cannot expect an improvement in economics. On the other hand, if it were possible to burn all 245U then the economics of utilizing natural uranium were virtually quardateed. The reference cost for fissile plutonium in oxide form is \$10.50 or fissile bu and for 235U it is \$3.50/gr 235U. The calculations were parfered with MERUS (2) and DIFIN (2) I did not consider the potential for improving the burnup capability of the fuel by intreasing the number of fissions in uranium as observed in irradiation experiments since this effect cannot be described quantitatively at the present time.

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$$157_{4} - _{0}1 = 7$$

The change in pluttenium inventory 6 over I years is

Fo(kg) or

$$\overline{F} = \frac{1}{2} F_0 . \tag{4}$$

The change in uranium inventory H over T calendar years is

$$H = F_0 . (5)$$

The annual cost of inventory and consumption, C, can therefore be expressed as

$$C = (I_0 - \frac{1}{2}T\delta I) \cdot iP^{Pu} + \delta I \cdot P^{Pu} + \frac{1}{2}F_0 \cdot i \cdot P^U + \frac{F_0P^U}{T}, \quad (6)$$

with i... annual interest rate, p^{Pu} ... \$/kg fissile plutonium, P^{U} ... \$/kg fissile uranium.

With I_0 , δI , I_0' , $\delta I'$ denoting inventory and inventory changes in a reactor using depleted and natural uranium, respectively, we can write the annual inventory and consumption cost for the LMFBR with depleted uranium, C^D , as

$$C^{D} = (I_{O} - \frac{1}{2}T\delta I) i \cdot P^{Pu} + \delta I \cdot P^{Pu} , \qquad (7)$$

and for the LMFBR with natural uranium, C^N , as

$$C^{N} = (I'_{0} - \frac{1}{2}T\delta I') i \cdot P^{Pu} + \delta I'P^{Pu} + \frac{1}{2}F_{0} \cdot i P^{U} + \frac{F_{0}P^{U}}{T} .$$
 (8)

The utilization of natural uranium instead of depleted uranium is justified if

$$C^{N} \leq C^{D} . (9)$$

We now introduce a critical residence time T such that

$$C^{N}(T_{crit}) = C^{D}(T_{crit}) , \qquad (10)$$

and determine T_{crit} from Eq. (10).

The charge in uranium inventory H over I calendar years is

The annual cost of inventory and continuition, G. can therefore be expressed as

with i... annual interest rate, p^n ... The fissile plutenius, p^0 ... The fissile uranium.

With I_0 , si, I_0^* , si, I_0^* , si' denoting inventory and inventory changes in a reactor using depleted and natural uranium, respectively, we can write the annual inventory, and consumption cost for the LMESR with deplated uranium, C_0^* , as

$$c^{D} = (1_{o} - 1_{1}1_{1}) + p^{Pu} + 61 + p^{Pu}$$
, (7)

and for the LMESR with natural unantum, CM, as

The utilization of natural uranium instead of depleted uranium is justified

We now introduce a critical restdence time T such that

and determine Torus Eq. (10).

With

$$p = \frac{i(I_0 - I'_0 - \frac{1}{2}F_0R) + (\delta I - \delta I')}{\frac{1}{2}i(\delta I' - \delta I)}$$
(11)

$$q = \frac{2F_0R}{i(\delta I - \delta I')}$$
 (12)

$$R = \frac{p^{U}}{p^{Pu}} \tag{13}$$

we obtain

$$T_{crit} = -\frac{p}{2} - \sqrt{\frac{p^2}{4} - q} > 0$$
 (14)

as the shortest residence time necessary to balance the cost for the utilization of natural vs. depleted uranium.

Because C^D is a linear function of T and C^N is a linear function of T plus a $\frac{1}{T}$ term, Eq. (1) has two solutions (see Fig. 1). The second solution T_2 has not been discussed since $T_2 > T_{\tt crit}$. It means, however, that for very long residence times the system with depleted uranium will be favored again. The reason for this behavior is the fact that the plutonium inventory changes decrease linearly with time whereas the change for the uranium consumption is proportional to $\frac{1}{T}$.

Because of the structure of C^N and C^D we can define an optimum time T_{opt} which assures the greatest savings in inventory and consumption cost whenever depleted uranium is replaced by natural uranium. It is obtained from

$$\frac{d(C^{N} - C^{D})}{dT} = 0 \tag{15}$$

da n

$$h = \frac{4(1^0 - 1^0 - 4e^0 8) + (91 - 91,)}{4(10^0 - 1^0 - 4e^0 8) + (91 - 91,)}.$$

$$R = \frac{pT}{pRu}$$

nladdo sw

$$T_{cete} = -\frac{p}{2} - \sqrt{\frac{p2}{4} - q} = 0$$
 (14)

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Because of the structure of \mathbb{C}^N and \mathbb{C}^D we can define an optimum time T_{opt} which assures the greatest savings in inventory and consumption cost whenever depleted uranium is replaced by natural uranium. It is obtained from

$$a(c^{N} - c^{N}) = 0$$

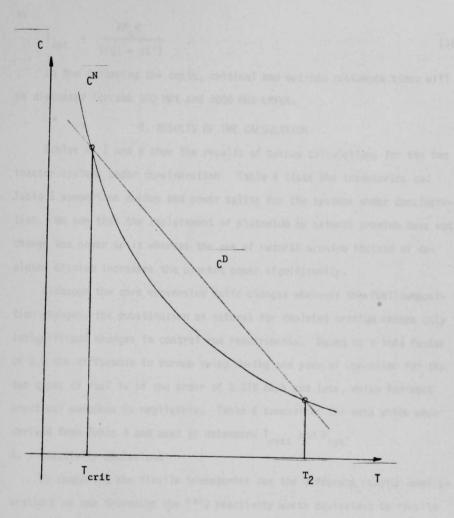


Figure 1. Schematic Representation of $\textbf{C}^{\textbf{N}}$ and $\textbf{C}^{\textbf{D}}$



figure 1. Schematic Representation of C" and C"

as

$$T_{\text{opt}} = \frac{2F_0R}{i(\delta I - \delta I')} \qquad (16)$$

In the following the costs, critical and optimum residence times will be discussed for the 500 MWt and 2000 MWt LMFBR.

5. RESULTS OF THE CALCULATION

Tables 4, 5 and 6 show the results of burnup calculations for the two reactor systems under consideration. Table 4 lists the inventories and Table 5 summarizes burnup and power splits for the systems under consideration. We see that the replacement of plutonium by natural uranium does not change the power split whereas the use of natural uranium instead of depleted uranium increases the blanket power significantly.

Although the core conversion ratio changes whenever the fuel composition changes, the substitution of natural for depleted uranium causes only insignificant changes in control rod requirements. Based on a load factor of 0.8 the difference in burnup swing during one year of operation for the two types of fuel is of the order of 0.01% $\Delta k/k$ and less, which for most practical purposes is negligible. Table 6 summarizes the data which were derived from Table 4 and used to determine $T_{\rm crit}$ and $T_{\rm opt}$.

A. Reactivity Equivalent

By comparing the fissile inventories for the different reactor configurations we can determine the 235 U reactivity worth equivalent to fissile plutonium. Table 7 shows these equivalents for the two reactor sizes.

About 1.2 kg 235 U has to be added to the core for each kg of core 239 Pu removed from the core to maintain the same criticality. If one tries to compensate for one kg of core 239 Pu by enriching the uranium in the blanket then 13.4 kg and 31 kg of 235 U are needed for the 500 MWt and 2000 MWt LMFBR respectively.

1 10 - 1131 - 240 T

(01)

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Although the core conversion ratio enanges whenever the duel composition changes, the substitution of natural for depleted grantum causes only insignificant changes in control rod requirements. Cased on a load factor of 0.6 the difference in burnup swing during one year of operation for the two types of tuel is of the order of 0.01% Ak/k and less, which for most practical purposes is negligible. Table 6 summarizes the data which were derived from Table 4 and used to determine T_{orts} and T_{opt}.

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TABLE 4. 500 MWt LMFBR Inventories

Case		1		2		3	4		
Irradiation Time, full power days	0	500	0	500	0	500	0	500	
Core Inventory, kg					30.1				
U-235 U-238 Pu-239 Pu-240 Pu-241 Pu-242	7.1 2363.1 557.5 75.6 0	3.9 2178.4 455.8 105.7 6.5 0.3	16.7 2361.8 550.2 74.6 0	9.3 2177.9 451.6 104.3 6.3 0.3	7.1 2364.3 556.5 75.4 0	4.0 2180.8 455.9 105.4 6.4 0.3	16.7 2363.0 549.1 74.4 0	9.3 2180.2 451.6 103.9 6.3 0.3	
total fissile Pu Blanket Inventory, kg	557.5	462.3	550.2	457.9	556.5	462.3	549.1	457.9	
U-235 U-238 Pu-239 Pu-240 Pu-241 Pu-242	10.0 3326.9 0 0 0	8.2 3239.1 74.9 1.54 0.0	10.0 3326.9 0 0 0	8.1 3239.4 74.7 1.5 0.0 0.0	23.4 3313.3 0 0 0	19.0 3226.1 74.2 1.5 0.0	23.4 3313.3 0 0 0	19.0 3226.4 74.0 1.5 0.0	
total fissile Pu	0	74.9	0	- 74.7	0	74.2	0	74.0	
Total Fissile Pu Inventory, kg	557.5	537.2	550.2	532.6	556.5	536.6	549.1	531.9	

TABLE 4. 500 Met EMPRR Inventories

TABLE 4 (cont'd) 2000 MWt LMFBR Inventories

Case		5	Market 1	6	Part class	7	8		
Irradiation Time, full power days	0	500	0	500	0	500	0	500	
Core Inventory, kg		COLUMN TO				J. Plants			
U-235 U-238 Pu-239 Pu-240 Pu-241 Pu-242	30.1 10021.2 1727.8 234.2 0	14.4 9033.5 1525.4 368.1 26.5 1.9	70.7 10017.6 1694.6 229.7 0	33.9 9033.8 1508.1 361.3 25.9 1.9	30.1 10022.0 1727.0 234.1 0	14.4 9037.5 1525.6 367.7 26.5 1.9	70.7 10018.6 1693.8 229.6 0	34.0 9037.4 1508.3 360.9 25.8 1.9	
total fissile Pu Blanket Inventory, kg	1727.8	1551.9	1694.6	1534.0	1727.0	1522.0	1693.8	1534.1	
U-235 U-238 Pu-239 Pu-240 Pu-241 Pu-242	18.6 6178.5 0 0 0	15.4 6034.6 125.2 2.4 0.0 0.0	18.6 6178.5 0 0 0	15.5 6034.8 125.0 2.3 0.0 0.0	43.4 6153.3 0 0 0	36.1 6009.4 124.9 2.3 0.0	43.4 6153.3 0 0 0	36.1 6009.7 124.7 2.3 0.0	
total fissile Pu	0	125.2	0	125.0	0	124.9	0	124.7	
Total Fissile Pu Inventory, kg	1727.8	1677.1	1694.6	1659.0	1727.0	1676.9	1693.8	1658.8	

TABLE 5. Burnup, Annual Burnup Swing and Power Split Summary

Time,		Power F	raction		Burnu	p, MWd/t		U ²³⁵ En	richment		_{U235}		Annual
fpd	T = 0		T =	500	T =	T = 500		T = 0	T =	500	Burnup, %		Burnup
Case	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Core	Blanket	Swing, % \Delta k/k
1	97.7%	2.3%	92.4%	7.6%	79,143	3,687	0.3%	0.3%	0.181%	0.25%	39.7%	16.7%	7.28
2	97.7%	2.3%	92.5%	7.5%	79,160	3,674	0.7%	0.3%	0.424%	0.25%	39.4%	16.7%	7.30
3	96.9%	3.1%	91.7%	8.3%	78,517	4,250	0.3%	0.7%	0.181%	0.597%	39.7%	14.7%	7.20
4	96.9%	3.1%	91.8%	8.2%	78,535	4,237	0.7%	0.7%	0.424	0.597%	39.4%	14.7%	7.22
5	99.17%	0.83%	97.11%	2.89%	81,725	2,938	0.3%	0.3%	0.159%	0.255%	47.0%	15.0%	5.35
6	99.17%	0.83%	97.11%	2.89%	81,731	2,933	0.7%	0.3%	0.374%	0.255%	46.6%	15.0%	5.41
7	98.86%	1.14%	96.76%	3.24%	81,446	3,480	0.3%	0.7%	0.159%	0.597%	47.0%	14.7%	5.31
8	98.86%	1.14%	96.76%	3.24%	81,452	3,474	0.7%	0.7%	0.374%	0.597%	46.6%	14.7%	5.37

TABLE S. Burnup, Annual Burnup Saring and Power Split Surmary

											5,37

TABLE 6. Summary of Input Data for Eqs. (7), (8), (14) and (16)

Case	I _o , kg	I _o -I(500), kg	δΙ,* kg	F _o , kg
1	557.5	20.3	11.86	22
2	550.2	17.6	10.28	16.7
3	556,5	19.9	11.62	23.4
4	549.1	17.2	10.04	40.1
5	1727.8	50.7	29.61	
6	1694.6	35.6	20.79	70.7
7	1727.0	50.1	29.26	43.4
8	1693.8	35.0	20.44	114.1

^{*}Based on a load factor of 0.8.

TABLE 5. Summary of Input Data for Eqs. (7), (8), (14) and (16)

Based on a load factor of 0.8.

TABLE 7. U²³⁵ Reactivity Worth Equivalents for 1 kg Pu²³⁹ in the Core

Size	Core	Radial Blanket
500 MWt	1.18 kg	13.4 kg
2000 MWt	1.22 kg	31 kg

TABLE 7. UZZZ Reactivity Worth Equivalents
for 1 kg Fu^{2 35} in the Core

B. Critical Residence Times

In the following, critical residence times will be discussed for the two LMFBRs as well as optimum residence times and potential fuel cycle cost savings. The discussion of these savings will be restricted to a discussion of fissile inventory and consumption charges.

Although burnup calculations were performed for all eight configurations, another restriction was introduced as a result of these calculations. Inserting the results from Table 6 into Eqs. (11) and (12) we see that q>0 in all cases but p<0 is fulfilled only for cases 2 and 6 (i.e., the exchanges of depleted uranium for natural uranium in the core). In all the other cases we obtain p>0 whichmeans $T_{\tt crit}<0$. The discussion of critical residence times and optimum residence times is therefore restricted to the cases where the depleted uranium in the core is replaced by natural uranium.

1) Reference conditions

The base case is characterized by the following assumptions

a.
$$P^{Pu} = $10^4$$

b.
$$P^{U} = $3.5 \cdot 10^{3}$$

c.
$$i = 0.15$$

Unless stated otherwise, these assumptions are used throughout the calculation.

2) C^D and C^N as a function of residence time

Both C^D and C^N decrease as the residence time increases. C^D decreases since the average fissile inventory decreases with increasing residence time. C^N decreases for the same reason, but in addition the consumption charge for C^N decreases with $\frac{1}{T}$. As shown in Tables 8 and 9 and Figs. 2 and 3, C^D decreases linearly with time whereas C^N decreases very fast for small values

Original Residence Times

In the following, critical residence times will be discussed for the two LMFBRs as well as optimum residence times and potential fuel cycle cost savings. The discussion of these savings will be restricted to a discussion of fissile inventory and consumption charges.

Although burmup calculations were performed for all aight configurations, unsertanter restriction was introduced as a result of these calculations. Insertang the results from Table 6 into Eqs. (11) and (12) we see that q > 0 in all cases but p < 0 is fulfilled only for cases 2 and 6 (i.e., the exchanges of deplated unanium for natural unanium in the core). In all the other cases we obtain p > 0 whithmeans I and optimum residence times is therefore restricted to the cases where the deplaced unanium in the core is replaced by natural unanium.

1) Reference conditions

The base case is characterized by the following assumptions

- -015 544
- or 2.23 = Vq . a
 - c. f = 0.15
- d. load factor = 0.8

intess stated otherwise, these assumptions are used throughout the calculation.

Both C^D and C^N decrease as the residence time increases. C^D decreases since the average fissile inventory decreases with increasing residence ting.

C^N decreases for the same reason, but in addition the consumption charge for a decreases with \(\frac{1}{2}\). As shown in Tables 8 and 9 and Figs. 2 and 3. C^D decreases linearly with time whereas C^N decreases very rast for small values.

TABLE 8. Fuel Inventory Plus Consumption Costs for the 500 MW LMFBR

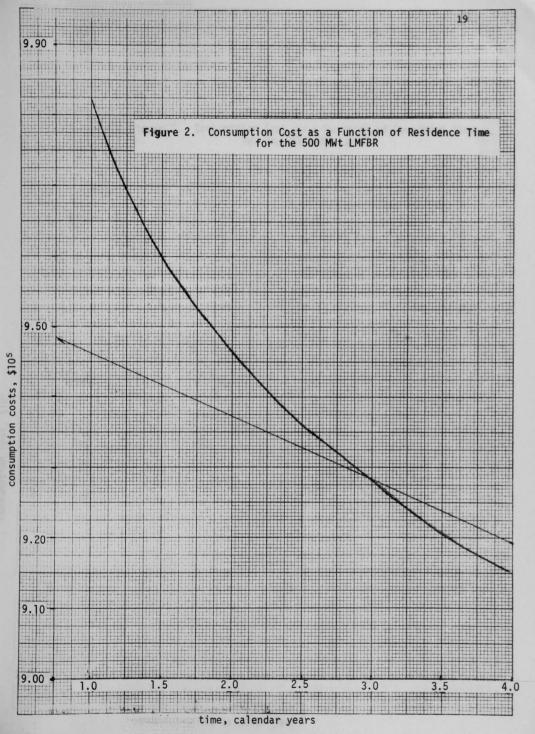
T, yrs.	C ^D (\$10 ⁵)	C ^N (\$10 ⁵)	C ^D - C ^N (\$10 ⁵)	$\frac{c^{D}-c^{N}}{c^{D}} \cdot 100\%$
1	9.46	9.83	-0.37	-3.9
1.5	9.42	9.60	-0.18	-1.9
2	9.37	9.46	-0.09	-1.0
2.5	9.33	9.37	-0.04	-0.4
3	9.28	9.29	-0.01	-0.1
3.5	9.24	9.22	0.02	0.2
4	9.19	9.16	0.03	0.3

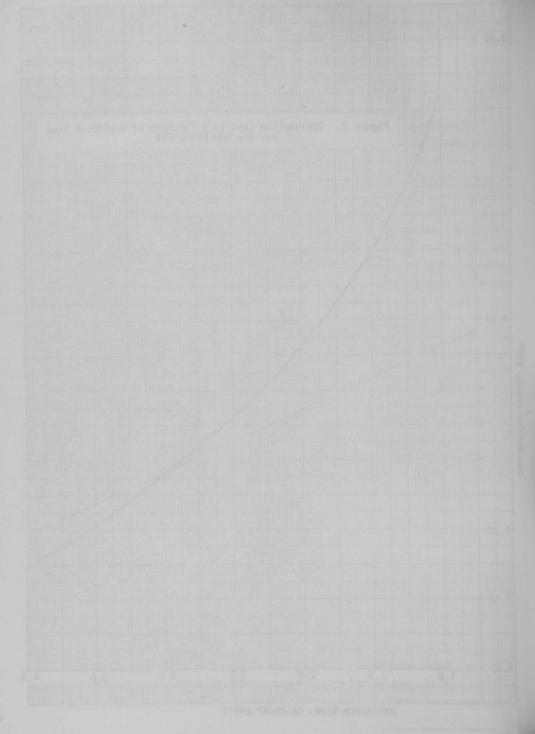
TABLE 8. Fuel Inventory Plus Consumption Costs for the 500 NW LMFBR

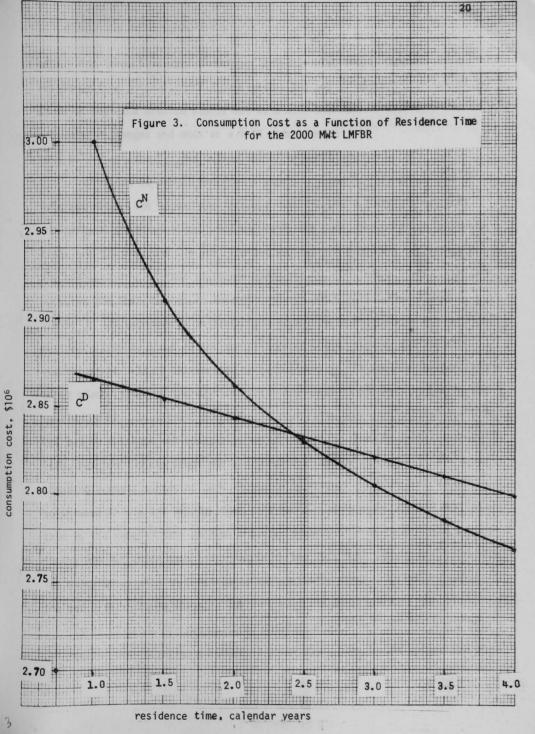
TABLE 9. Fuel Inventory Plus Consumption Costs for the 2000 MWt LMFBR

T, yrs.	C ^D (\$10 ⁶)	C ^N (\$10 ⁶)	$C^{D} - C^{N}(\$10^{6})$	$\frac{C^{D}-C^{N}}{C^{D}} \cdot 100\%$
1	2.87	3.00	-0.13	-4.5
1.5	2.85	2.91	-0.06	-2.1
2	2.84	2.86	-0.02	-0.7
2.5	2.83	2.83	0	0
3	2.82	2.81	0.01	0.4
3.5	2.81	2.79	0.02	0.7
4	2.80	2.77	0.03	1.1

TABLE 9: Fuel Inventory Plus Consumption Costs For the 2000 MRt CMFOR







of T. For large T values, C^N changes linearly with time. Considering a residence time interval from 1 to 4 years, the use of natural uranium instead of depleted uranium starts out as a 4.5% increase in inventory and consumption changes and ends as a 1.1% reduction.

3) T_{crit} and T_{opt} as a function of interest rate

Tables 10 and 11 and Fig. 4 show T and T as a function of interest rate. The higher the interest rate the shorter are the critical and optimum residence times. For our reference case, the critical residence times are 3.1 yrs. and 2.4 yrs. for the 500 MWt and 2000 MWt, respectively. The corresponding optimum residence times are 7.0 yrs. and 6.1 yrs. Furthermore, we see that changes in interest rate do not significantly affect T and T ont. An increase in interest rate from 7.5% to 15% reduces the critical residence time by about 8% and the optimum residence time by 29% for both reactor sizes. It is interesting to note that T_{crit} is smaller for the larger LMFBR sizes, although the uranium reactivity worth is slightly higher in the smaller LMFBR. In a small reactor, the reactivity contribution from the blanket due to fissions and especially reflection of neutrons is higher than in a large reactor. Since these nuclear properties change only very little by exchanging a small amount of core plutonium by natural uranium, 235U should be worth more in a small reactor than in a large reactor assuming that the spectrum is the same in both systems. On the other hand, the spectrum is harder in the 500 MWt LMFBR than the spectrum in the 2000 MWt. This tends to decrease the worth of uranium in relation to the plutonium worth. As Table 7 shows, the net effect favors slightly the 235U worth in small LMFBRs.

Table 12 shows the depletion of natural uranium in a 500 MWt and a 2000 MWt reactor over a period of 500 full power days. Due to the softer spectrum

of T. for large T values C dringer linearly with time. Considering a residence time-interval from 1 to 6 years, the use of natural unantum instead of diploted unantum starts out as a 4.5% increase in inventury and contampeten charges and ends as a 1.15 reduction.

3) T and T as a function of interest rate

interest rate. The higher the dopore t rate the shorter are the critical and epithmun residence times. For our reference case, the critical residence times are 3.1 year and 2.00 MHt. respectively.

The corresponding optimum refinence times are 3.0 year and 5.7 year. Butthermore, we see that changes in interest rate do not significantly affect I orter and 3.0 years and 3.1 years that on the course of the content of the cont

nore, we see that changes in interest rate from 7.5% to 15% reduces the critical residence time by about 6% and the optimum residence time by 25% for both reactor sizes. It is interesting to note that T_{art} is smaller for the larger reactor the uranitum reactivity worth is tlightly bigher in the larger test due to fitsing, in a smaller invest, in a smaller than the place only note that a smaller invest, in a smaller invest, in a smaller invest, in a smaller invest, and the smaller invest, in a smaller invest, and the smaller invest, in a smaller invest, and the smaller invest, in a smaller invest, in the spectrum in t

Table 12 shoet the depletion or netural grantum (n a 500 Met edu a 2000 Met esactor over a period of 500 full cower days. Due to the softer spectrum

TABLE 10. Critical Residence Time T $_{
m crit}$ and Optimum Residence Time, T $_{
m opt}$, as a Function of Interest Rate for the 500 MWt LMFBR

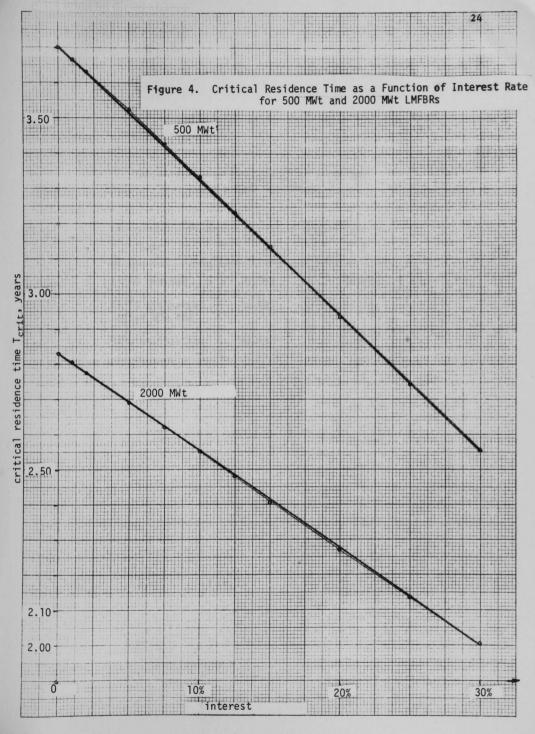
Interest Rate i	T _{crit} , yr.	T _{opt} , yr.
0	3.70	
0.01	3.67	27.2
0.02	3.63	19.2
0.05	3.52	12.2
0.075	3.43	9.93
0.10	3.33	8.60
0.125	3.23	7.69
0.15	3.14	7.02
0.20	2.94	6.08
0.25	2.74	5.44
0.30	2.55	4.97

3.70	

TABLE 11. Critical Residence Time T $_{
m crit}$ and Optimum Residence Time, T $_{
m opt}$, as a Function of Interest Rate for the 2000 MWt LMFBR

Interest Rate i	T _{crit} , yr.	T _{opt} , yr.
0	2.83	
0.01	2.80	23.8
0.02	2.78	16.8
0.05	2.69	10.6
0.075	2.62	8.69
0.10	2.55	7.52
0.125	2.48	6.73
0.15	2.41	6.14
0.20	2.27	5.32
0.25	2.14	4.76
0.30	2.01	4.34

MBUE 11. Critical Residence Time Torte and Optimum
Residence Time, I as a Function of
Interest Rate for the 2000 MM: 18708



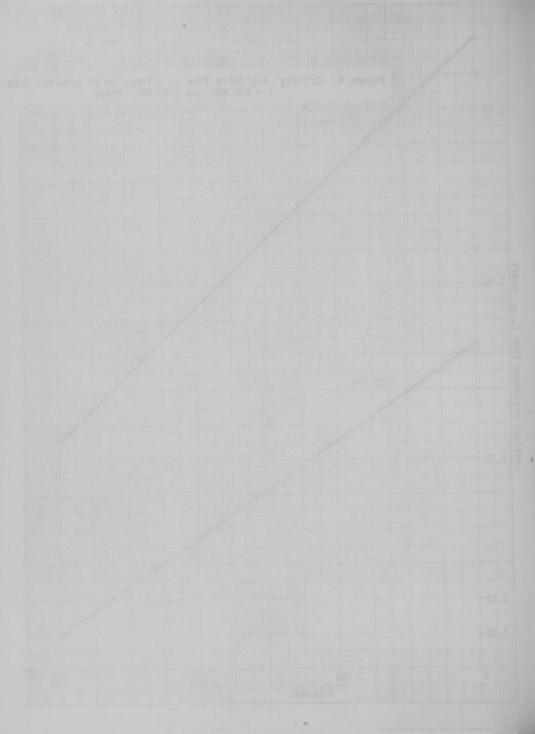


TABLE 12. ²³⁵U Utilization in a 500 MWt and a 2000 MWt LMFBR

Case	2	6
% ²³⁵ U charged	0.700	0.700
% ²³⁵ U discharged after 500 fpd	0.424	0.374
²³⁵ U utilization	39.4%	46.6%

TABLE 12. 2850 Utilization in a 500 MMs Limes

and the smaller leakage, significantly more ^{235}U is burned in the large LMFBR than in the small LMFBR. This explains why the critical residence time in the 2000 MWt is about 30% shorter than in the 500 MWt reactor.

4) $T_{\rm crit}$ and $T_{\rm opt}$ as a function of the 235 U price Tables 13 and 14 and Fig. 5 show critical and optimum residence time as a function of the 235 U price. While the effect of changes in the interest rate has only little effect on $T_{\rm crit}$ and $T_{\rm opt}$, the 235 U price is the key parameter in assessing the utilization of depleted vs. natural uranium. Increasing the 235 U price from \$3.50/gr 235 U to \$4.0/gr 235 U increases the critical residence time by more than 20% and the optimum residence time by 7% for both reactor sizes.

6. CONCLUSIONS

Under certain conditions, it is more economical to use natural uranium instead of depleted uranium in the LMFBR. A critical residence time T_{crit} can be defined such that the costs for inventory and consumption are the same in a LMFBR with natural uranium and one using depleted uranium. The use of natural uranium is restricted to the core region. In a small reactor system (500 MWt for core and radial blanket which corresponds to a total reactor output of approximately 200-250 MWe) the residence time for the fuel has to be at least three years to justify the utilization of natural uranium instead of depleted uranium on economical grounds. The larger LMFBR (i.e., 2000 MWt which is equivalent to approximately 800 MWe) permits critical residence times of less than 3 years for fuel assemblies containing natural uranium in order to stay under the inventory and consumption cost of a LMFBR using depleted uranium. Shorter critical residence times must be expected if natural uranium is being used for fuel assemblies in the center core region

Tables 13 and 14 and Fig. 5 show critich! and optimin restounce time as a function of the PPSU price. While the effect of changes in the interest rate has only little effect on Texts and Texts and Texts and Texts and Texts are the the the price of deplaced to natural draction. Increasing the Sau price from \$3.50/gr \$750 to \$3.0/gr \$750 the deplaced to the critical residence time by note than \$00 and the optimizers.

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TABLE 13. Critical Residence Time T $_{\tt crit}$ and Optimum Residence Time T $_{\tt opt}$ as a Function of ^{235}U Price for the 500 MWt LMFBR

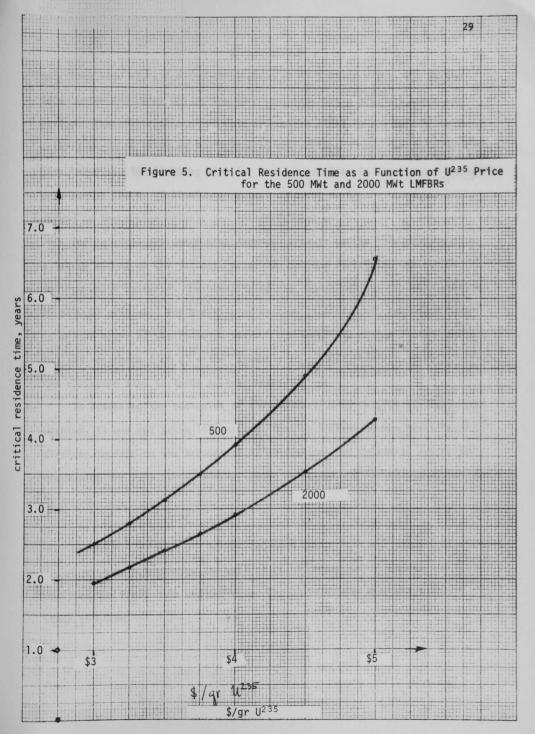
U ²³⁵ Price \$/gr. U ²³⁵	T _{crit} , yr.	T _{opt} , yr.
3.00	2.50	6.50
3.25	2.80	6.77
3.50	3.14	7.02
3.75	3.50	7.27
4.00	3.90	7.51
4.50	4.91	7.96
5.00	6.58	8.39

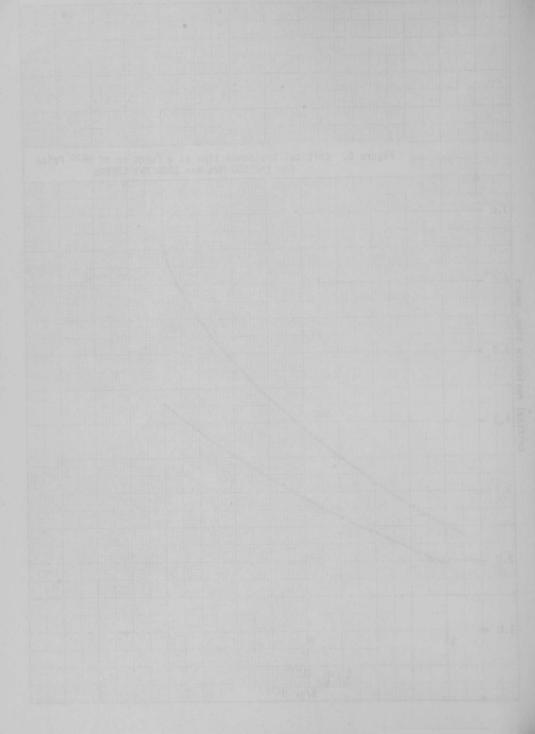
MBLE 13. Colifcal Residence Time T_{cric} and Optimum Residence Time T_{opt} as a Punction of Page Price for the 500 Mar LMPRR

TABLE 14. Critical Residence Time T $_{\rm crit}$ and Optimum Residence Time T $_{\rm opt}$ as a Function of $^{235}\rm U$ Price for the 2000 MWt LMFBR

U ²³⁵ Price \$/gr. U ²³⁵	T _{crit} , yr	T _{opt} , yr
3.00	1.96	5.69
3,25	2.18	5.92
3,50	2.41	6.14
3.75	2.66	6.36
4.00	2.92	6.57
4.5	3.53	6.96
5,00	4.28	7.34

AGES 14. Entited Residence Time T and Outhouse
Residence Sime T as a function of star





only (see Fig. 6), since the utilization of ²³⁵U is more than 70% at the core center and below 30% at the core periphery for a 500 full power day period. The utilization of ²³⁵U in assemblies close to the core-blanket interface can be improved by increasing the residence time for those assemblies, however, the limiting time for those assemblies is usually not the peak burnup limit. Estimates on actual critical residence times, however, depend on the design details and the enrichment split.

The critical residence time depends strongly on the ²³⁵U price and to a lesser extent on the interest rate. An optimum residence time can be defined which maximizes the benefits of the replacement of depleted uranium by natural uranium. For the reactor systems studied, this residence time is of the order of six to seven years. Our knowledge of the factors affecting the residence time of a fuel assembly in a LMFBR, however, would restrict the residence time to three to four years.

In assessing the economics of the utilization of natural vs. depleted uranium, it was not taken into account that by increasing the fraction of fissions in ^{235}U on the account of ^{239}Pu fissions the potential exists for increasing the peak burnup limit. These relations are not yet quantitatively known.

Acknowledgement

I wish to acknowledge the work of Dr. A. Olson and I. Lawson who modified the REBUS code and performed the calculations upon which this study is based.

only (see Fig. 6), since the utilization of fine core chee 70% at the core canter and melow 20% at the core canter and melow 20% at the core canter and melow 20% at the core canter at the attilization of "U"in essentials close to the core-blankst letters can be improved by increasing the restdence time for those desembles is usually not the park burnup limit. Estimates on actual critical residence blanch towards, howevery depend on the design details and the environment.

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